# The Use of a Flash Vaporization System
# With Liquid Hydrocarbon Fuels in a Pulse Detonation Engine

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## Abstract

In recent research,[1,2] liquid fuel droplets were found to hinder the detonation process in a pulse detonation engine (PDE). In the current work, multi-phase effects are eliminated with a flash vaporization system that vaporizes the liquid fuels prior to mixing with air. Hydrocarbon and air mixtures have been transitioned from deflagration to detonations previously,[1] but exhibited long ignition and deflagration to detonation transition (DDT) times. Here, two liquid hydrocarbon fuels, with different octane numbers (ON), are detonated with air in a PDE to determine the effect of octane number on the ignition time and the DDT time. The premixed, combustible mixture fills the PDE tubes via an automotive valve and cam system described in detail elsewhere.[3] N-heptane (ON-0) and isooctane (ON-100) are evaluated individually to determine the effects of automotive octane number on pulse detonation engine combustion performance. The ON has been considered previously[4] as an acceptable criterion in determining the detonability for PDEs, and it is derived based on the tendency to "knock" or detonate relative to isooctane in an automotive engine application.
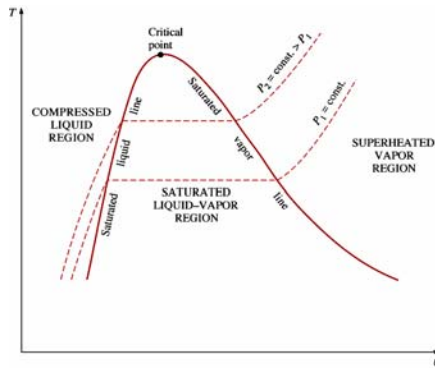
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The goal of this research is to show that a flash vaporized liquid hydrocarbon fuel system can provide the fuel and air homogeneity required to achieve detonations. The octane number is studied to determine its influence on the ignition and DDT time for hydrocarbon fuels.

The flash vaporization system provided an outstanding method for achieving the desired mixing and vaporization, and the systems operating points matched well with the liquid vapor equilibrium model results. The ignition times showed little dependence on fuel injection temperatures or octane number and no droplet effects were noted. The DDT trends were octane number dependent and the isooctane was difficult to detonate with wave speeds below the stable Chapman-Jouget (CJ) wave speeds. The heptane readily detonated and produced wave speeds at or above CJ.

## Background

Combustion performance of a liquid hydrocarbon fueled pulse detonation engine is hindered by the presence of fuel droplets and long ignition times[5,6]. The presence of droplets indicates that locally fuel rich and fuel lean regions exist, and that the overall mixture lacks the required homogeneity for ideal combustion performance. The presence of droplets increases ignition time because the initial energy deposit (spark) must evaporate any surrounding fuel droplets to create an explosive mixture. A high-pressure fuel flash vaporization system was designed and built to eliminate the time required to evaporate liquid fuel droplets.

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Figure 1. T-u diagram for simple substance[7].



Figure 2. Automotive knock event.

To remove the evaporation times, the fuel is injected into air at a temperature above the boiling temperature at the highest pressure the fuel air mixture will encounter before combustion. When the high pressure, high temperature fuel is injected into a lower pressure air stream via a pressure atomizing nozzle, the fuel will immediately vaporize and thereby remove the time required to evaporate the fuel. The phase change process is shown in Fig. 1 for a simple (single component) substance. As the pressure applied to the fuel goes higher, the saturation temperature also rises until both converge at the critical point. The pressure used during the tests is well above the critical pressure of each fuel and allows the fuel to be heated without boiling until reaching the supercritical temperature of the fuel. An added benefit is improved mixing of the fuel and air mixture. Since the flash vaporization system injects gaseous fuel, it will more readily achieve the desired fuel air homogeneity required to ignite and transition a detonation.

Octane number

In a spark initiated (SI) automobile engine, knock is noted by the noise emitted when the fuel air mixture inside the engine ignites prematurely relative to the desired burn rate initiated by the spark advance on the engine. However, compression heating of the unburned mixture from both the advancing piston and the evolving confined flame front can auto ignite the fuel air mixture (Fig. 2). The premature ignition event releases the stored chemical energy in the fuel at a rate between 5 and 25 times faster than the spark initiated rate[8]. A susceptibility to knock may represent a sensitively to more quickly allow detonations to transition when a deflagration is channeled through an obstacle such as a Schelkin spiral.
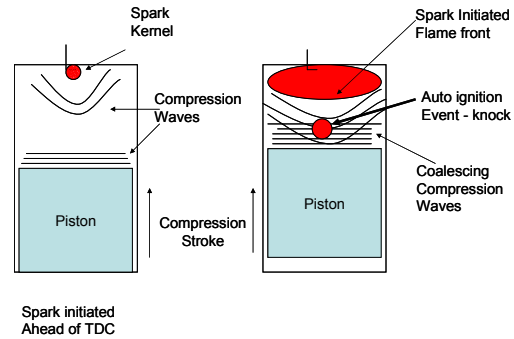
The fuel's octane number relates the mixture's resistance to knock relative to a mixture of isooctane (ON=100) and n-heptane (ON=0). The higher the number, the more resistant the fuel is to exhibit the phenomena. Two methods are commonly used to determine the fuel octane number. The Research Method[9] tests fuels at representative low speed city driving conditions, and the Motor Method[10] tests fuels at representative high speed highway driving. The resulting research octane number (RON) and motor octane number (MON) are used to determine an antiknock index or AI. The historical standard ASTM Specification D 439 is used for determining the antiknock index by simply averaging the RON and MON[11].

| Fuel | Formula | RON | MON | AI |
|------|---------|-----|-----|-----|
| n-heptane | $C_7H_{16}$ | 0 | 0 | 0 |
| isooctane | $C_8H_{18}$ | 100 | 100 | 100 |

Table 1. Octane numbers[11].

## Experimental Setup

This research was performed in the Air Force Research Laboratory (AFRL) Pulse Detonation Research Facility at Wright Patterson AFB, Ohio. The facility incorporates two electrically driven camshafts situated in a General Motors Quad 4 head. Four thrust tubes are attached where pistons would normally interact with the head and valves. A single thrust tube with a 5.2 cm diameter, 182.9 cm long steel pipe is fired at a frequency of 15 Hz. The rotating cams provide a three-part cycle with equal time (120 degrees) to fill, fire, and purge the tube. The manifold pressure behind the valves is adjusted to provide the correct fill volume at the desired operating frequency. The fill volume is defined as the volume of the thrust tube when the fuel air mixture expands to atmospheric pressure at the open end of the tube.
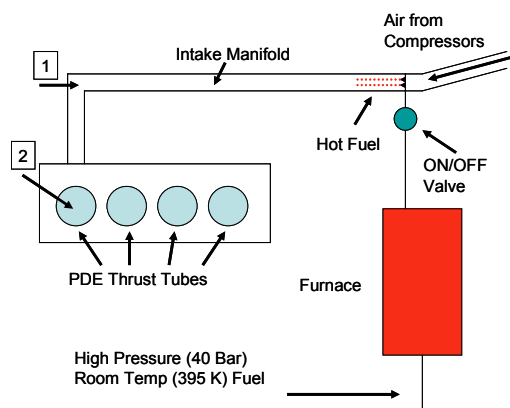
Figure 3. Flash vaporization system.

The flash vaporization system stores high pressure, high temperature fuel in the furnace and when a pneumatically operated ball valve opens, the fuel flows to three pressure atomizing fuel nozzles which are situated to inject the fuel tangentially into the main air flow (Fig. 3). The fuel air mixture has a mixing length of 1.52 meters before being fed into the thrust tube for combustion. The air is heated to 311K (+/-1K) prior to entering the manifold and mixing with fuel. In Fig. 4, pressure measurements during the filling process are recorded in the manifold (location 1 in Fig. 3) and at the closed end of the thrust tube (location 2 in Fig. 3). The ignition delay from the time the valve closes until the time the spark is deposited is 10 milliseconds. The delay enhances the ignition and DDT performance by utilizing the returning compression wave seen in the blue head pressure trace in Fig. 4. The zero time is denoted at the point the intake valves close.
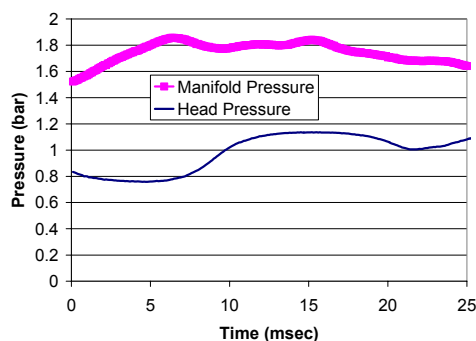


Figure 4. Premixed manifold and head pressure traces (absolute) for 15 Hz test conditions.

Fuel Air Premix Conditions

The fuel and air are premixed in the manifold (Fig. 3) prior to being feed into the PDE thrust tube. The pressure conditions in the

intake manifold are critical to understanding whether or not the fuel vapor will condense back into liquid due to any heat transfer or pressure effects.

The National Institutes of Standards and Technology (NIST) program SUPERTRAPP version 3.1 was used to determine how much liquid was in the premixed fuel air mixture in the manifold if left at the specified pressure and temperature until it reached equilibrium. The program uses the thermo physical properties of hydrocarbon mixtures database and computes the vapor-liquid equilibrium using the Peng-Robinson model[12].

The stoichiometric fuel air mixture was input into the program at a pressure of 2.0 bar which is slightly above the maximum pressure observed in Fig. 4. The mixture temperature was varied to determine the percentage of liquid fuel present at equilibrium.
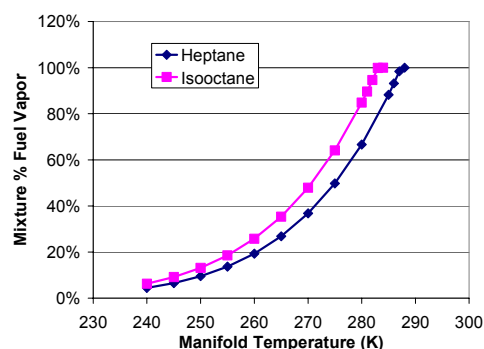


Figure 5. Equilibrium liquid vapor state for a stoichiometric fuel Air mixture at 2.0 bar.

Since both fuel and air are mixed as gases, they should reach equilibrium quickly and remain gaseous as long as the mixture temperatures do not drop below those shown in Fig. 5. If the temperatures in the manifold drops below 285 K, the fuel vapor may condense back into liquid.

Fuel Conditioning

Heating fuel above 450 K can cause particulate formation and carbon deposits on metal surfaces[13,14]. To prevent the fuel from reacting with any dissolved oxygen, the dissolved oxygen was removed by sparging the fuel with nitrogen prior to pressurization and heating. In sparging, nitrogen is bubbled through the liquid fuel to agitate and replace any dissolved oxygen. In the ullage region above the liquid, the nitrogen leans out the oxygen and eventually replaces all the oxygen in the fuel tank.

Figure 6. Fuel tank sparge spiral.

The photo in Fig. 6 shows the sparging spiral with drilled holes that nitrogen was fed through to agitate the fuel. Tests were performed with air saturated fuel to determine the amount of nitrogen to fully deoxygenate the fuels. The fuels were sampled at different times with a gas chromatography machine until no oxygen could be measured. To prevent the reaction with metals, silicon based coatings were applied to all hot section components including the fuel nozzles. The coating provides a very thin non-reactive surface which prevents any contact between the fuel and the metals.

Constant Ignition Energy

A 12 volt DC automotive digital ignition system supplied power to the spark plug. The system provided a series of 105 – 115 milli-Joule sparks[15] into the hydrocarbon fuel air mixture via a capacitance discharge. The number of sparks per cycle was verified using a 27,000 frame per second camera and noted a 250 μs duration pulse every 1.1 milliseconds (+/-37μs). A total of four sparks are deposited during each ignition event at the operating frequency of 15 Hz.

## **Results**

Flash Vaporization System Validation

The flash vaporization system worked well in providing a gaseous fuel air mixture. This was verified from the manifold temperature changes as the fuel injection temperature was increased. For both heptane and isooctane, the required temperature to be fully flash vaporized was above 395 K (Fig. 7). Below the 395 K injection temperature, the air temperature in the manifold drops due to the enthalpy of evaporation from the evaporating liquid droplets. Above 395 K, no energy is required to evaporate

the droplet and excess fuel enthalpy is used to raise the manifold air temperature slightly.
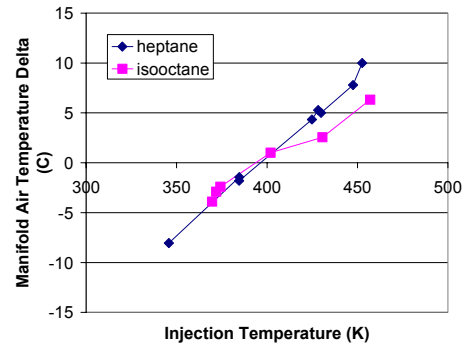

Figure 7. Manifold air temperature change after fuel injection.

The heptane and isooctane showed similar temperature changes after injection in the manifold. This is expected since the two fuels have nearly the same boiling point at the maximum pressure in the manifold of 1.85 bar listed in Tab. 2 below. The boiling point also denotes exactly the crossing point for which the fuel increases or decreases the mixture temperature in the manifold. Since the fuel air mixture was above 285 K (Fig.5), the mixture is assumed to be completely vaporized for all test points.

| Fuel | Boiling Temperature (K) @ 1.85 bar | CJ Detonation Wave Speed (m/s) |
|---|---|---|
| n-heptane | 393.4 | 1793.7 |
| isooctane | 395.0 | 1791.8 |

Table 2. Fuel boiling point and CJ detonation wave speeds[19]

Tests were performed to note any changes in the nozzle flow patterns at liquid injection temperatures below and above the boiling temperature. In Fig. 8, water is injected at room temperature, and the spray is very wide with individual droplets still discernible. In Fig. 9, the spray is more tightly confined and has features consistent with a supersonic jet, thus denoting a gaseous injection. The phase change occurs from the static pressure drop while accelerating to the throat of the constant area nozzle.

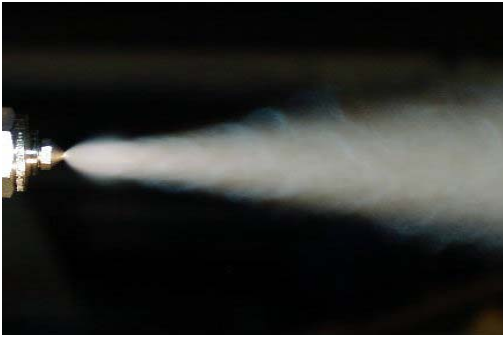Figure 8. High pressure atomized water at 20C and 43 bar.



Figure 9. Flash vaporized water at 200C and 43 bar.

Ignition times

Two methods are used to determine the ignition time from when the initial spark energy is deposited. The first is a dynamic pressure transducer (Fig 10). The transducer records pressures in the PDE head and corresponds to the pressure rise due to the constrained heated gases in the closed end of the PDE tube. Opposite the pressure transducer is a photo multiplier tube (PMT) with a 307 nanometer filter. The sensor reacts to the radiative energy associated with OH production. The OH radical is in abundance during hydrocarbon combustion and gives a second method to determine the ignition time. The combination of these two techniques to determine ignition time has been used elsewhere[16].

The combustion data from the pressure and OH sensors is shown in Fig. 11. The ignition event is said to have occurred at the initial point when the pressure rises sharply, which for this data occurs around 9 milliseconds after the spark energy has been deposited into the fuel air mixture in the head of the thrust tube.

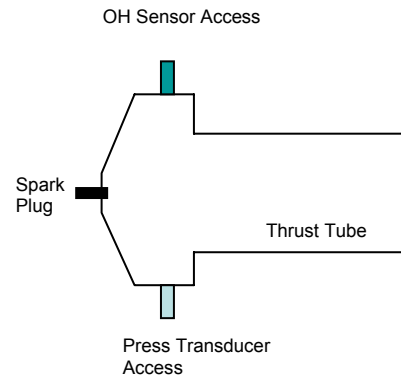Likewise, the OH trace drops sharply when the PMT senses light in the correct wavelength.



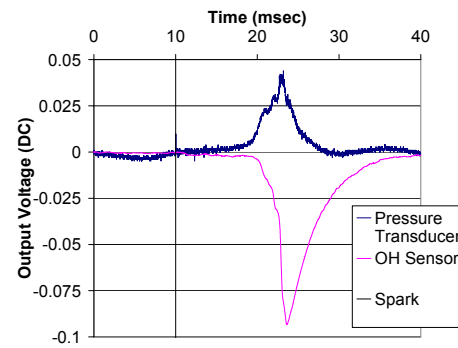Figure 10. Sensor locations in PDE head.



Figure 11. Ignition event after spark deposit at 10 milliseconds.

The ignition times for both sources are determined using an in-house program which filters the noise from the signal and looks for a slope change above or below a manually designated threshold.
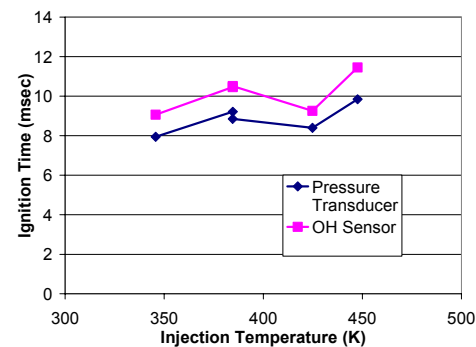


Figure 12. Measured ignition times for heptane.

The measured heptane ignition times from both the pressure trace and OH sensor were within 10 to 20 percent of one another with the OH sensor lagging. The ignition times did not show the expected dependency on injection

temperature. Lower fuel injection temperatures and a shorter mixing length in the manifold may allow a droplet effect on ignition time. Similar ignition times were seen for the isooctane data in Fig. 13. The octane number did not strongly influence the ignition times.
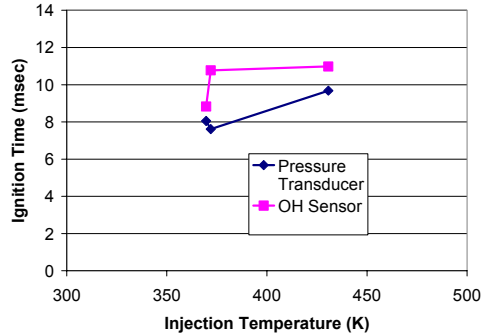


Figure 13. Measured ignition times for isooctane

The DDT time was determined as a time of flight through the DDT obstacle, a 1.22 meter Schelkin like spiral. The faster the DDT occurs, the shorter the time to travel through the spiral. The DDT time was computed from the time ignition was first observed to the time a detonation wave exited the spiral and was detected by an ion sensor. The results are shown in Fig. 14 below and show the influence of octane number.
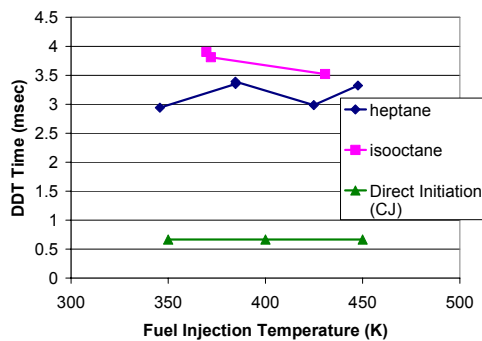


Figure 14.  DDT Time for each Fuel

The isooctane took roughly 500 microseconds longer to traverse the spiral than the heptane. The wave speeds also reflect the difficulty in detonating the isooctane. Combustion performance of a PDE is primarily based on whether or not a detonation occurs within the thrust tube.  The detonation is said to have occurred if the combustion wave speed is at the Chapman-Jouguet (CJ) point (Tab. 2).  The CJ point is based on the Hugoniot curve, which relates continuity, energy, momentum, and the perfect gas law for a one dimensional, steady,

planar detonation wave.  The CJ point denotes the conditions of maximum heat transfer rate from the energy stored in the fuel and converting it to a hypersonic detonation wave.  This occurs at the point of minimum entropy for the process mathematically, and additionally, it is the equilibrium point for the process[18].
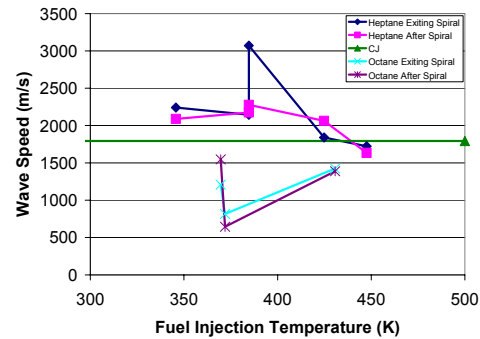


Figure 15. Detonation wave speeds observed for each fuel.

The detonation wave speeds are measured using ion probes downstream of the DDT spiral. No influence was seen in injecting the fuel at a higher temperature (Fig. 15).  The heptane wave speeds were at or above the CJ wave speeds.  Several super CJ speeds were observed at the 385 K injection temperature. These were transverse waves formed as the detonation transitioned through the spiral.  The wave speeds after the spiral settled out to roughly 10 percent above CJ.  The 450 K injection data were observed with a lower fill ratio and the mixture was more lean at the end of the tube, though a near CJ (- 9 percent) was still achieved. The isooctane was difficult to detonate and showed wave speeds below than the stable CJ wave speed.

## Conclusions

The liquid hydrocarbon fueled flash vaporization system worked well to provide a fully vaporized, homogenous mixture that is required for a detonation wave. The fuel injection temperature raised or lowered the mixture temperature downstream of injection with the fuel's boiling temperature as the crossing point.

The correlation between octane number and ignition and DDT times was also studied. The ignition times did not show octane number dependence. The DDT trends and magnitudes did follow the expected octane number influence. The isooctane (ON=100) was more difficult to

detonate with wave speeds below the stable CJ wave speeds. The heptane (ON=0) readily detonated and saw wave speeds at or above CJ.

Future work will be performed at a wider range of injection temperatures and with lower vapor pressure fuels.

### Acknowledgements

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